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4 µm Surface-emitting Quantum Cascade Laser using Photonic Crystal

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Abstract

We design and fabricate the surface-emitting quantum cascade lasers using InGaAs photonic crystals buried with InP. Pulsed lasing operation emitting at around 4 µm with a laser beam divergence angle of less than 2 degrees is achieved.

1. Introduction

Quantum cascade lasers (QCLs) are important mid-infrared light sources for many laser-based applications such as gas sensing and biological sensing [1-3]. Desirable specifications of QCLs for such applications are high power, single mode operation and low divergent beam shape. Surface emitting laser is a good candidate to realize those requisite qualities. As a surface-emitting lasers, vertical cavity surface-emitting laser (VCSEL) is widely used in the wavelength range from visible to near infrared today [4]. However, this VCSEL structure which uses distributed Bragg reflector (DBR) cannot be applied to QCL in principle due to the transverse magnetic polarization selection rules based on the inter-subband transitions.

To archive the surface emitting with QCLs, using photonic crystals (PCs) instead of the DBR is the attractive solution [5-7]. PC-QCLs is expected to achieve both single mode operation together with narrow diverging surface emission, and to reduce the manufacturing cost because of the excellence in mass productivity. In addition, enlargement of the devise size is effective to improve heat dissipation, enabling higher output power.

Although very high wall plug efficiency (WPE) of 22% was reported recently [8], the WPE of QCLs are basically not as high as that of visible or near infrared semiconductor lasers. Therefore the heat dissipation of the device is very important when applying a high current to produce high output power. In this work, we develop and fabricate a surface-emitting QCL device structure using photonic crystals (PCs) that are buried with regrowth InP layer to improve heat dissipation of the device.

2. Device Fabrication

Figure 1 shows a cross-sectional schematic of the designed surface-emitting QCL using PCs. The QCL structure was epitaxial grown on an n-doped InP substrate by solid-source molecular beam epitaxy (MBE). The whole laser structure consisted of an 1.0 µm InGaAs buffer layer, a 2.5 µm Si-doped InP cladding layer, a 0.3 µm InGaAs guide layer, an 1.6 µm active region, and an 1.0 µm InGaAs layer for PCs. The active region consists of 30 stages AlInAs/InGaAs strain balanced structure which designed to emit at a wavelength of around 4.4 µm. It has already been confirmed in advance that the oscillation gain wavelength of the QCL epi-wafer is around 4.4 µm at 77 K by fabricating a conventional ridge-guide edge-emitting QCL device [9]. We designed square-lattice PCs with the shape of circle pillar whose diameter is around 1.4 µm and the pitch is around 1.1 µm preparing for this oscillation gain wavelength. The PCs are formed right above the active region in order to enhance the influence of the PCs on the active region. After Electron Beam lithography to make SiO_x hard mask, PCs pillars are formed by inductively coupled plasma (ICP) dry-etching with Cl_2 at a temperature of 150 °C on the top 1.0 µm InGaAs layer. As the controllability of size and shape of the PCs is important, wet surface treatment with phosphoric acid after ICP dry-etching is carefully and shortly performed to avoid shape change. Then the PCs are buried with a 3.0 µm Si-doped InP layer followed with a 0.1 µm Si-doped InGaAs layer by metal-organic vapor phase epitaxy (MOVPE). Since the morphology of the regrown layer can be affected if the layer containing Al is at the outermost layer during MOVPE regrowth burying, the depth of dry-etching is determined as 700 nm without penetrating to the active region. Figure 2 shows a cross-sectional scanning electron microscopy (SEM) of the buried InGaAs PCs. No voids or visible defects that adversely affect heat conduction are observed and the shape of PCs remains as designed. Square shapes laser cavity mesas with dimensions of around 500 µm × 500 µm is formed by around 6 µm depth ICP dry-etching till beneath the active region. After SiO_x insulator for the current contraction to the mesa formed, epi-side of the laser is completely covered by a Ti/Au contact metal. On the substrate side, a square opening shape contact metal is formed in order to extract QCL emission from the substrate surface. After processing, the laser is cleaved and epi-down mounted on a CuW heat sink.

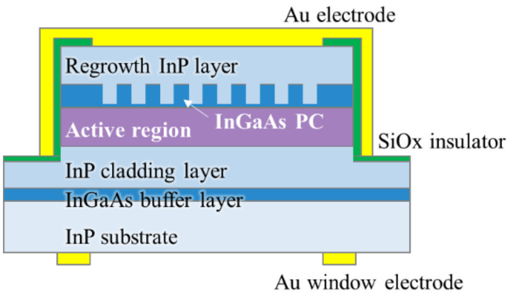

Fig. 1 Cross sectional schematic of the surface emitting QCL

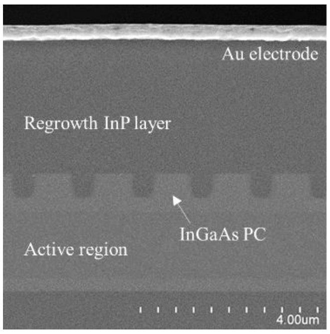

Fig. 2 SEM image of the InGaAs pillar PC buried with InP

3. Results and Discussion

Measurements are performed in the direction perpendicular to the substrate at the temperature of 77 K under pulsed operation with a pulse width of 300 ns and a duty ratio of 1.5 %. Figure 3 shows the measured current-light-voltage (ILV) characteristics and lasing spectrum (inset). The threshold current is around 5 A, the threshold current density is around 2 kA/cm^2 and the output power is up to 10 mW. The emission peak wavelength of around 4.43 µm is slightly different from the designed wavelength of 4.4 µm, which is caused by the slight deference in design parameters such as refractive index. By the results of the far field pattern measurement, surface emitted beam with extremely small divergence angle (<2˚) is observed.

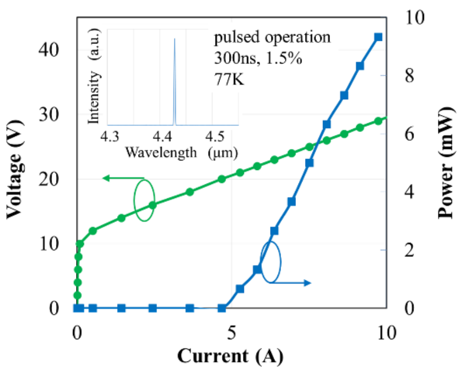

Fig. 3 Measured ILV characteristics and lasing spectrum

4. Conclusion

We have designed and fabricated the surface-emitting QCL using InGaAs PCs buried with regrowth InP. Surface-emission lasing is achieved under pulsed operation with the wavelength around 4.43 µm. The beam divergence angle of the surface emission of less than 2° is observed. Surface-emitting QCL device structure using PCs has high potential for realizing both single mode operation together with narrow diverging surface emission.

Acknowledgements

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